MP MASTER
MA34450

Voice (Intl): 516.467.8479
Voice (USA): 516.467.8400
Fax: 516.467.8558
Email: rjaniec@ifi.com
World Wide Web: www.ifi.com
Richard Janiec
Sales Manager
731 Union Parkway
Ronkonkoma, Long Island, New York 11779-7414

TEM CELL
MODEL CC105EXX

OPERATING AND MAINTENANCE
INSTRUCTIONS

SERIAL NUMBER: A781-1297

731 UNION PARKWAY
RONKONKOMA, N.Y. 11779
TEL 516-467-8400 FAX 516-467-8558

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SECTION 1.0

INTRODUCTION

Congratulations on the purchase of your new Crawford Cell from Instruments For Industry, Inc. The Crawford Cell was originally developed at the National Bureau of Standards, Boulder, Colorado, as a simple and relatively inexpensive electromagnetic test chamber usable up to a frequency of several hundred megahertz, and subsequently engineered for production by Instruments For Industry, Inc. The cell can be used for susceptibility testing of electronic hardware, circuit boards, cables, connectors, or to irradiate biological, mineral or other types of samples. It can also be used in a reciprocal mode to detect and measure radiation from any object placed within the unit.

The device is essentially an expansion of a coaxial cable used in the Transverse Electromagnetic or TEM mode. The internal field can be determined either by direct measurement or by calculation from a known applied voltage. It is terminated in its characteristic impedance of 50 Ohms and presents a flat input impedance characteristic over its frequency range. There is no limit to the lower frequency of use, but the upper frequency is limited by the first wave guide mode that may be developed within the structure.

SECTION 2.0

WARRANTY INFORMATION

Instruments For Industry, Inc. (IFI) warrants each product of its manufacture to be free from any defect in material and workmanship for a period of one year from shipment to the original purchaser. All warranty returns, however, must first be authorized by our factory office representative. Refer to the Service Section for information on how to return items for warranty repair.

Warranty liability shall be limited to repair or replacement of, or part thereof, which proves to be defective after inspection by IFI. This warranty shall not apply to any IFI product that has been disassembled, modified, physically or electrically damaged or any product that has been subjected to conditions exceeding the applicable specifications or ratings.

IFI shall not be liable for any direct or consequential injury, loss or damage incurred through the use, or the inability to use, any IFI product.

IFI reserves the right to make design changes to any IFI product without incurring any obligation to make the same changes to previously purchased units.

This warranty is the full extent of obligation and liability assumed by IFI with respect to any and all IFI products. IFI neither makes, nor authorizes any person to make, any other guarantee or warranty concerning IFI Products.

SECTION 3.0

DESCRIPTION AND OPERATION

3.1 DESCRIPTION

The cells are manufactured in a range of sizes but can be constructed to almost any dimensions desired. Table One lists the dimensions of IFI's standard production Crawford Cells, gives the upper frequency limit and shows the dimensions of the largest recommended object that should be placed in the unit. The dimension D given in this table is the spacing between the top of the septum and the inside surface at the top of the unit. This dimension is used to compute the field strength developed internal as will be described later. The unit is perfectly symmetrical in its construction; either end can be used as the input. The connectors are type "N" and are mounted on transitions which convert the coaxial input to the parallel plate or flat septum which is used as a center conductor. There are two screws at the top of this transition section which may be removed to provide access to the fastenings which connect the rear of the connector assembly to the septum. There is one nylon screw on the bottom of this transition which is a support for the septum. Slightly further, at the small end of the tapered section, are two removable plates. These provide access to adjustable sections of the septum which are used for impedance matching purposes. In addition to these there is a removable plate near the top of one end which can be used for the installation of connectors, when cables are to be brought into the unit. There is a door on the side which contains a piece of conducting glass and is lined with a metex gasket. The hinges on this door are adjustable and the gasket pressure may be altered by tightening the hinges. The test cell may be used with either the door at the top, or with the unit turned upside down and the door on the bottom, depending entirely on the users requirements. There may be an occasion where the test object is so heavy as to tend to distort the septum. When this occurs, the unit should be turned upside down and the test object placed in the bottom section.

The test cell when first received should be examined for physical damage both internally and externally. If any is encountered, the manufacturer should be notified immediately. If it is desired to make electrical checks on a unit, both a voltage standing wave ratio meter and a time domain reflectometer should be used. For the voltage standing wave ratio measurements the instrument should be connected directly to the test cell, as the VSWR of the cell is the same order of magnitude as the additional connectors, cables and connection between the test instrument and the cell will give erroneous readings. If a Time Domain Reflectometer (TDR) is used, it should be remembered that the rise time of the pulse from the reflectometer will usually contain components beyond the usable frequency range of the Crawford Cell. This will result in spurious responses in the TDR display that will usually appear on the output side of the center line of the unit, in other words, the cell should be measured by looking at the portion from the input to the center line only. The test equipment then may be connected to the other end and that end examined. The TDR data supplied with the unit is measured with a pulse which has a rise time of 1 ns.

The equipment to be installed inside the unit should not occupy volume greater than a third of the available space. Cables to the unit should be routed perpendicularly to the field and their effect checked with the time domain reflectometer. The test object should be placed in the center of the cell between the septum and the top of the unit. It may be mounted on a small block of dielectric with low dielectric constant. The field generated inside the cell is perpendicular to the septum and has a magnitude equal to the applied voltage divided by the cell spacing "D" as illustrated in Table One. The field in volts per meter may also be calculated from the expression,

$$E = \frac{P \times R}{D}$$

where P is the power flowing through the unit and R is the resistance level at the point of the unit under test.

A detailed discussion of this test cell and its use is given in the IEEE Transactions on Electromagnetic Compatibility, for November, 1974, Page 189, by M.L. Crawford. A copy of the article is provided in Appendix A. The article contains analysis, setup instructions, and descriptions of the fields that may be generated inside the cell. The IFI test cell conforms to the configuration of Figure 4 within this report.

3.2 FIELD STRENGTH IN STANDARD TEM CELLS

The field strength for standard TEM cells is shown below, however, the field strength, for any sized TEM cell, can be easily calculated with the following simple formula:

$$E = e/d$$

where:

E = Field strength in volts/meter
e = Applied rms voltage
d = distance between center conductor and septum

For example:

Example 1:
With e = 10 volts
and d = 1 meter,
Using the formula E = e/d
E = (10 volts/1 meter) or 10 v/m

Example 2:
With e = 10 volts
and d = 0.5 meter,
Using the formula E = e/d
E = (10 volts/0.5 meter) or 20 v/m

Example 3:
With e = 10 volts
and d = 0.1 meter,
Using the formula E = e/d
E = (10 volts/0.1 meter) or 100 v/m

Example 4:
With e = 10 volts
and d = 2 meters,
Using the formula E = e/d
E = (10 volts/2 meters) or 5 v/m

3.3 MULTIPLYING FACTOR FOR STANDARD TEM CELLS

Multiply the applied rms voltage by the cell factor in Table One to determine the effective field strength in the cell.

Use the power/voltage relationship, $E^2 = (PxZ)$, if a measured power is to be converted to voltage.

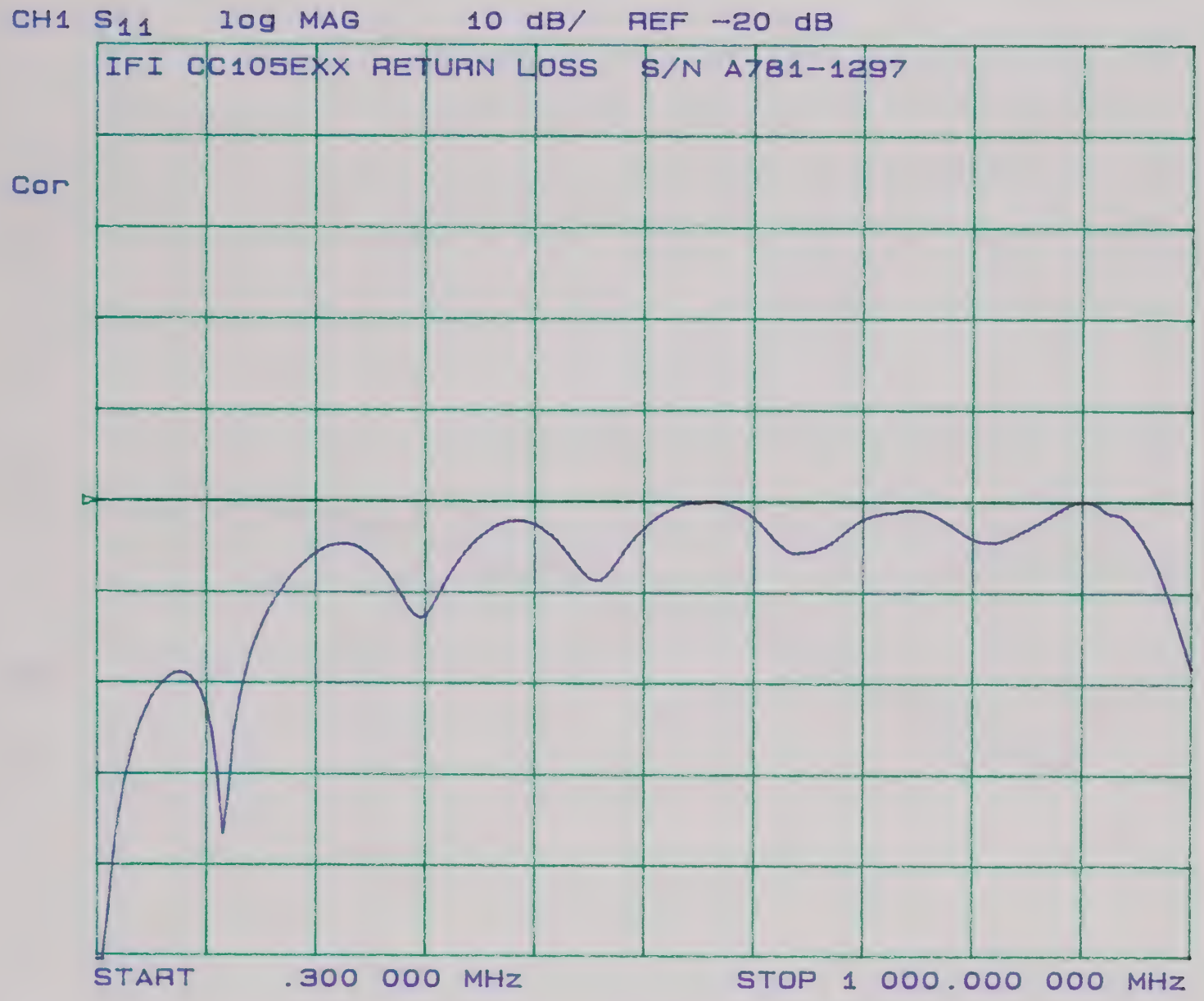
Where:

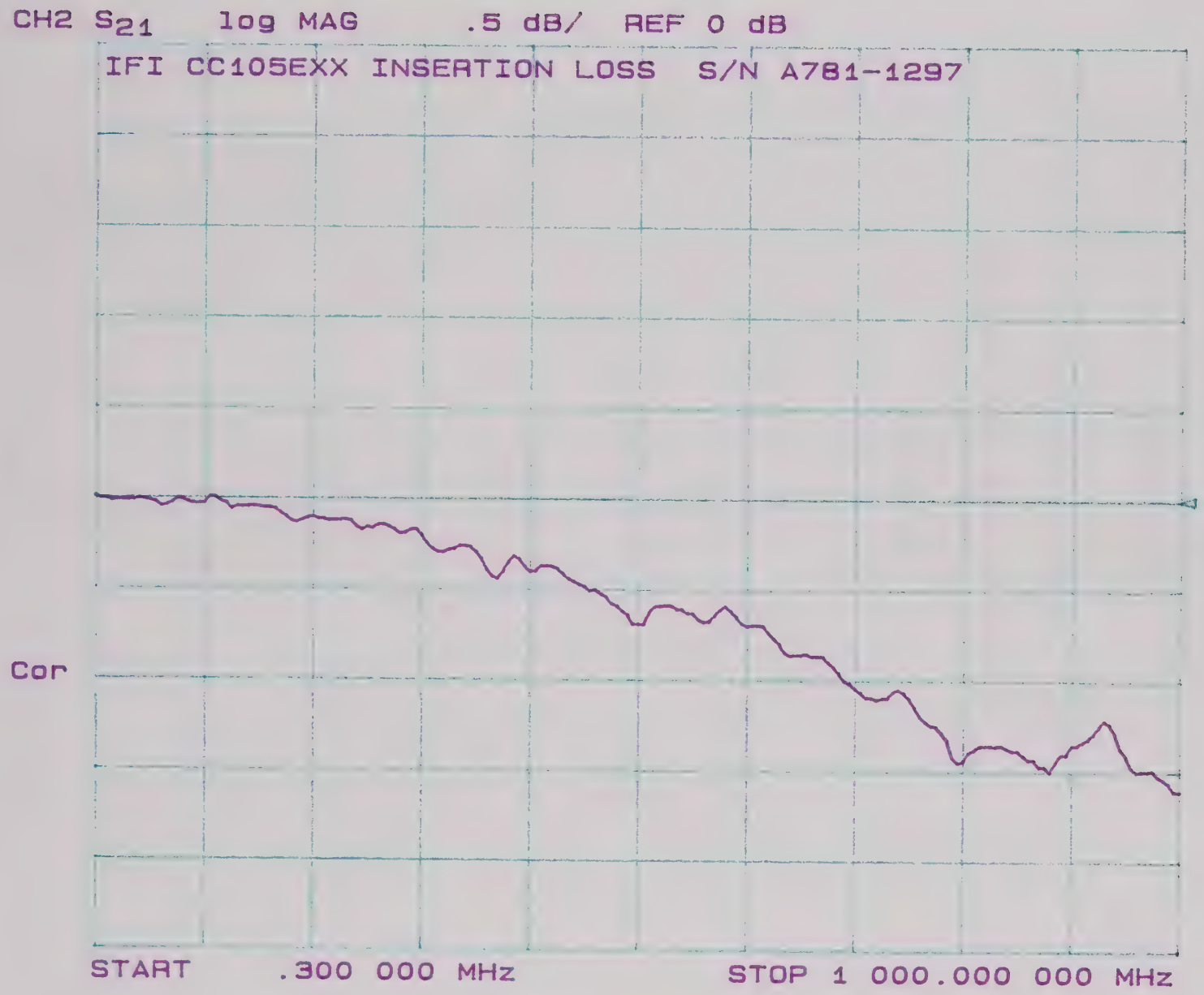
P = Power in Watts
Z = 50 Ohms (cell impedance)

TABLE ONE

TEM CELL FACTORS

MODEL	SPACING (D)	CELL FACTOR
CC100S	1.0 meter	1.00
CC100	0.667 meter	1.50
CC101S	0.9 meter	1.11
CC101	0.6 meter	1.67
CC101.5S	0.6 meter	1.67
CC101.5	0.4 meter	2.50
CC102S	0.45 meter	2.22
CC102	0.3 meter	3.34
CC103S	0.3 meter	3.34
CC103	0.2 meter	5.00
CC104	0.15 meter	6.67
CC105	0.12 meter	8.34
CC105SEXXDW	0.18 meters	5.57
CC108	0.075 meter	13.34
CC110	0.06 meter	16.75


CH1 S11 log MAG 10 dB/ REF -20 dB
IFI CC105EXX RETURN LOSS S/N A781-1297
Cor
START .300 000 MHz
STOP 1 000.000 000 MHz


CH2 S21 log MAG .5 dB/ REF 0 dB
IFI CC105EXX INSERTION LOSS S/N A781-1297
Cor
START .300 000 MHz
STOP 1 000.000 000 MHz

APPENDIX A

IEEE TRANSACTIONS ON

ELECTROMAGNETIC COMPATIBILITY

November 1974
Pages 189 - 195

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151 TOLEDO STREET, FARMINGDALE, N.Y. 11735
(516) 694-1414

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Generation of Standard EM Fields Using TEM Transmission Cells

MYRON L. CRAWFORD

Abstract—A new technique developed at the National Bureau of Standards (NBS) for establishing standard, uniform, electromagnetic (EM) fields in a shielded environment is described. The technique employs transverse electromagnetic (TEM) transmission cells that operate as 50 Ω impedance-matched systems. A uniform TEM field is established inside a cell at any frequency of interest below that for which higher order modes begin to propagate. Standard field strength levels from 10 μV/m to 500 V/m can be established with uncertainties of less than 1.0 dB to 2.0 dB inside the NBS cells for frequencies from dc to 500 MHz. The cells are especially useful for calibrating EM radiation hazard meters, for emission and susceptibility testing of small to medium sized equipment, and for special low level calibration of very sensitive field strength meters.

I. INTRODUCTION

THE proliferation of electronic/electromechanical systems in our environment is causing a rapid rise in the level and number of potential interfering signals. Compatible operation of such systems in the presence of electromagnetic (EM) interference is a function of their EM susceptibility, the ability to accurately measure and control it, and/or to effectively shield against it.

A number of techniques exist for establishing known, uniform levels of electromagnetic energy for susceptibility testing over limited frequency ranges and for limited applications [1]–[3]. For example, high level fields can be generated quite accurately above a few hundred megahertz using standard gain horns and below a few megahertz using parallel plate lines. Both these techniques are widely used, but suffer a major disadvantage; they radiate electromagnetic energy into the surrounding space which may interfere with the measurements, be hazardous to the operator, or interfere with other experiments being conducted within transmission range.

The technique described in this paper contains the EM field inside the transmission cell. It is extremely broad band in frequency, being limited only by the waveguide multimode frequency associated with the cell size. Construction costs of the cells are minimal and the use of expensive anechoic chambers or shielded enclosures are unnecessary. The cells can be used to establish known field strength levels from 10 μV/m to 500 V/m with uncertainties less than 1.0 dB to 2.0 dB (depending on frequency). The cells are especially useful for calibrating EM radiation hazard monitors, for equipment emissions and susceptibility testing, and for special low-level sensor calibrations.

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The author is with the National Bureau of Standards, Boulder, Colo. 80302.

II. DESCRIPTION, DESIGN, AND EVALUATION OF THE TEM CELLS

The design of the cells was patterned somewhat after a large cell constructed for the USAF School of Aerospace Medicine at Brooks AFB [4]. The NBS cells were designed as shielded chambers for EM susceptibility and emissions testing of test specimens, and for calibration of EM field probes. A cross sectional view of a typical cell is shown in Fig. 1. The cell consists of a section of rectangular coaxial transmission line tapered at each end to adapt to standard coaxial connectors. The line and tapered transitions have a nominal characteristic impedance of 50 ohms along their length to insure minimum voltage standing wave ratios (VSWR). The EM field is developed inside the cell when RF energy is coupled to the line from a transmitter connected at the cell input port. A matched 50 ohm termination is connected to the output port. The fields inside the cell are monitored using special electric and magnetic field probes designed and constructed by NBS [5]. A differential power measuring system, designed by NBS [6] for measuring energy absorbed from the cell by test subjects, can also be used to determine the field strength if the cell's impedance is known.

Experience with the Brooks AFB cell showed that at frequencies for which only the principal wave (TEM mode) propagates through the cell, a reasonably uniform electric field could be generated. The main limitation of their cell was its large size, restricting its usefulness to frequencies below 50 MHz. A series of smaller cells were developed at NBS to increase this range up to 500 MHz. The major design considerations were:

1) maximize usable test cross sectional area;
2) maximize upper useful frequency limit;
3) minimize cell impedance mismatch or voltage standing wave; and
4) maximize uniformity of EM field pattern characteristic of the cell.

The cells were designed using experimental modeling and the approximate equation for the characteristic impedance of shielded strip line [4]

$$z_0 \simeq \frac{94.15}{(\epsilon_r)^{1/2}\left[\dfrac{w}{b(1-t/b)} + \dfrac{C_f'}{0.0885\epsilon_r}\right]} \quad \text{(ohms)} \quad (1)$$

where ϵ_r is the relative dielectric constant of the medium between the conductors, C_f' is the fringing capacitance in

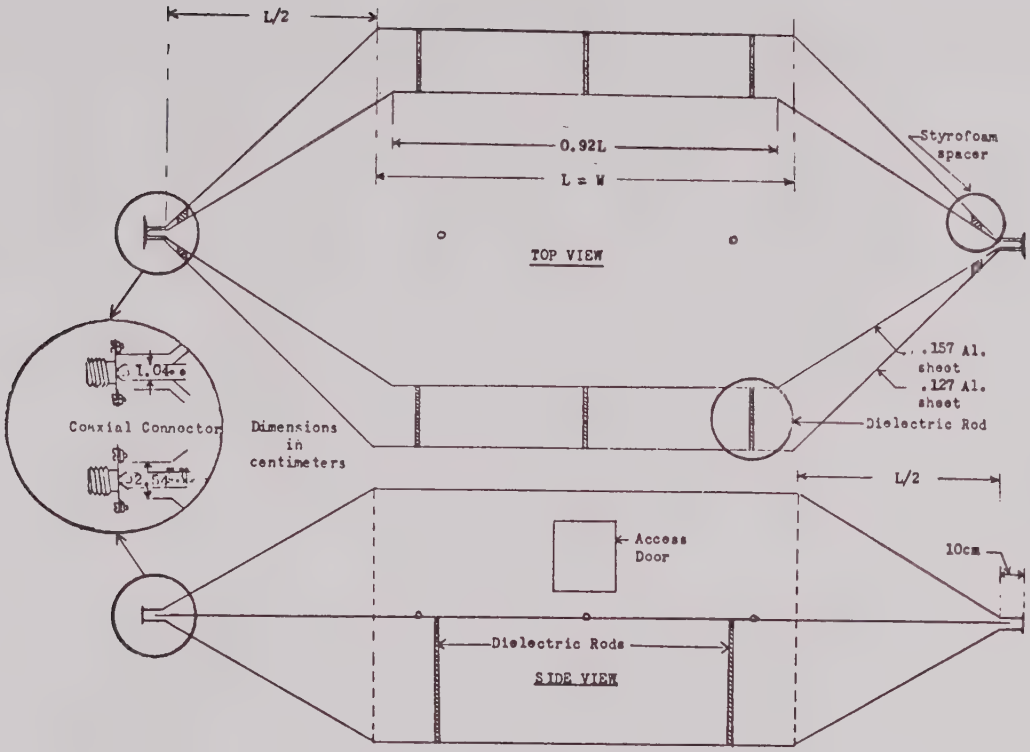

Fig. 1. Design for rectangular TEM transmission cell.

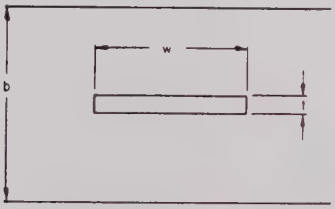

Fig. 2. Shielded strip line.

picofarads per centimeter, and w, b, and t are shown in Fig. 2.

The problem of modifying the shielded strip line into a "rectangular coaxial" line was primarily one of determining experimentally the value of C_f'. This was done using a time domain reflectometer (TDR) to evaluate small scale models of cells with the cross sectional geometry shown in Figs. 3 and 4. C_f' was found to be approximately equal to 0.087 pF/cm, respectively. Dimensions for b were determined from the design criterion that as much as 1/3 [1] of the volume between the septum and outer plates can be occupied by the equipment under test (EUT) to meet design considerations 1, 3, and 4. Once b was calculated, an experimental estimate of C_f' determined, and an available metal thickness t selected, w can be calculated from (1), assuming a nominal 52 ohms for the line characteristic impedance. (Fifty-two ohms

[1] The one third factor is considered a maximum. The impedance loading effect from inserting the EUT should not exceed a few ohms if a reasonable VSWR and EM field perturbation is to be maintained.

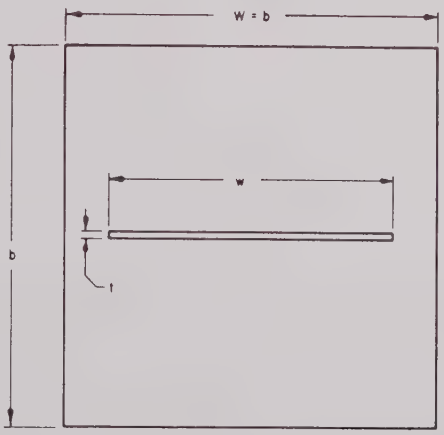

Fig. 3. Cross sectional view of optimum geometry of rectangular transmission line for maximum test area and frequency.

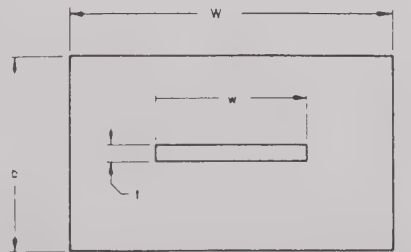

Fig. 4. Cross sectional view of rectangular transmisison line with improved E field uniformity.

TABLE 1
TEM CELL DIMENSIONS

Cutoff/ Multimode Frequency (MHz)	Square Cell (Fig. 3) Plate Separation b (cm)	w (cm)	t (cm)	C'_f (pF/cm)	Rectangular Cell (Fig. 4) Plate Separation b (cm)	w (cm)	t (cm)	C'_f (pF/cm)
100	150	123.83	.157	.087	90	108.15	.157	.053
300	50	41.28	.157	.087	30	36.05	.157	.053
500	30	24.77	.157	.087	18	21.83	.157	.053

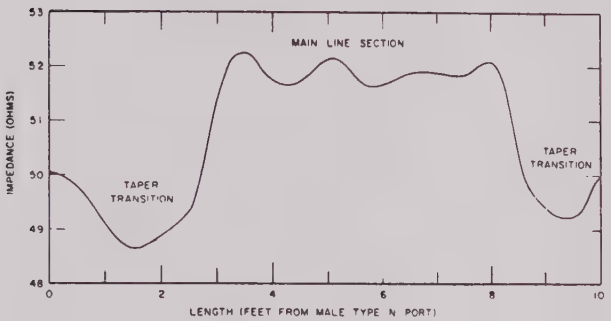

Fig. 5. Time domain reflectometer trace of distributed impedance of empty cell. (Form factor Fig. 3.)

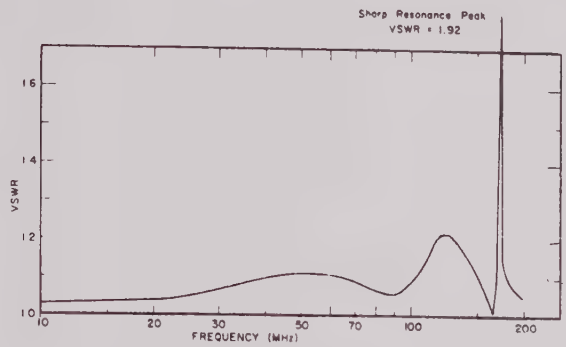

Fig. 6. Port input VSWR of empty cell. (Form factor Fig. 3.)

was chosen to allow for some impedance loading effect when inserting the EUT inside the cell.) Table 1 gives the dimensions for constructing the two cell forms with specified upper frequency limits. The TDR was then used to make refinements by trimming w until the proper characteristic impedance was obtained.

The cross section of Fig. 3 is used at high frequencies where maximum cell size is limited and requires some compromise in electric field uniformity. The cross section of Fig. 4 achieves greater field uniformity at the cost of vertical test space restriction. Fig. 5 gives a typical TDR trace of the distributed impedance along the length of a cell of Fig. 3 cross section, and Fig. 6 shows the VSWR as seen at the cell's input and output ports.

MAPPING THE FIELDS INSIDE THE CELLS

Measurements were made using a calibrated short dipole to probe the electric field inside the empty cells. The variations in relative field strength versus position were determined in the longitudinal, transverse, and vertical directions within the cells. The electric field E is essentially vertically polarized in the region near the center of the cells and gradually becomes horizontally polarized as one moves in the horizontal direction toward the gap at the side. Both vertical and horizontal components of E were measured at each point to determine the total electric field, $E = (E_v^2 + E_H^2)^{1/2}$ where E_v and E_H are in phase. The electric field distributions for each form factor are shown in Figs. 7 and 8. The electric field in the test regions shown is primarily vertically polarized or $E_v \gg E_H$. The relative field distribution is independent of the magnitude of the test field used and the frequency so long as the frequency is less than the first order TE mode (TE_{10}) cutoff frequency given by the following equation:

$$(f_c)_{10} = c/2W. \tag{2}$$

The equation for determining the cutoff frequency for any higher order mode in general is given by

$$(f_c)_{m,n} = \frac{c(b^2m^2 + W^2n^2)^{1/2}}{2bW}. \tag{3}$$

For (2) and (3), c is the velocity of propagation of light $\simeq 3.0 \times 10^8$ m/s, b and W are as shown on Figs. 5 and 6, and m and n are integers related to the half sine variations of the field in the vertical and transverse directions. If higher order modes are allowed to propagate, the field configuration, which is the vector sum of each contributing mode, no longer has the simple pattern shown in Figs. 7 and 8. Thus higher order modes would greatly complicate interpretation of the measured results of the cell.

Variations in the electric field strength for the empty cells were less than 2 dB for the cross section of Fig. 3 and less than 1 dB for the cross section of Fig. 4 over the area typically occupied by the EUT. Inserting the EUT shorts out part of the electric field due to the metal in the case and increases the field strength proportional to the percentage cross section occupied. Fig. 9 shows an example of the results of inserting a solid metal case inside a cell of the form factor shown in Fig. 3. This case occupied 1/3 the vertical separation between the upper wall and

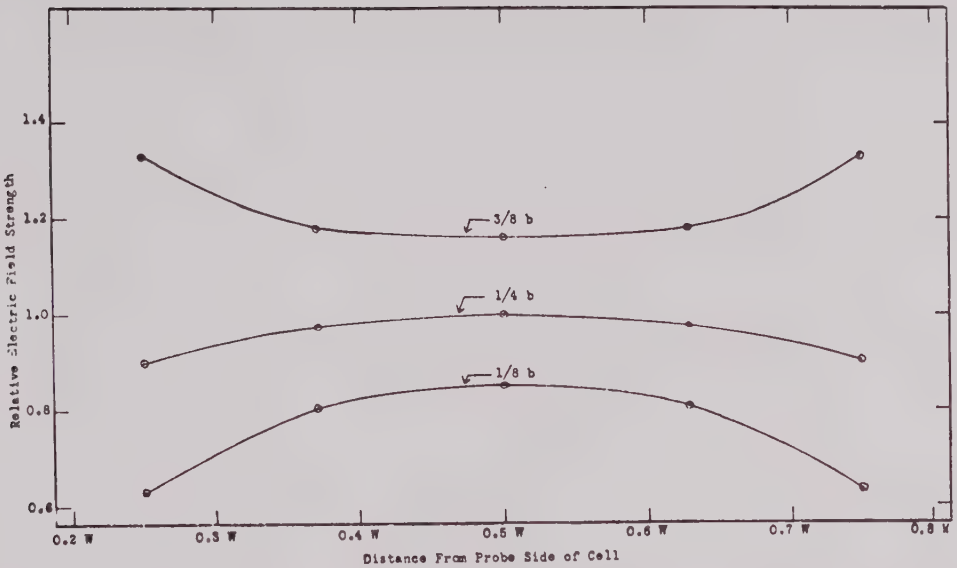

Fig 7. Relative electric field distribution inside cell. Cross sectional cut through upper half at center of cell. (Form factor Fig. 3.)

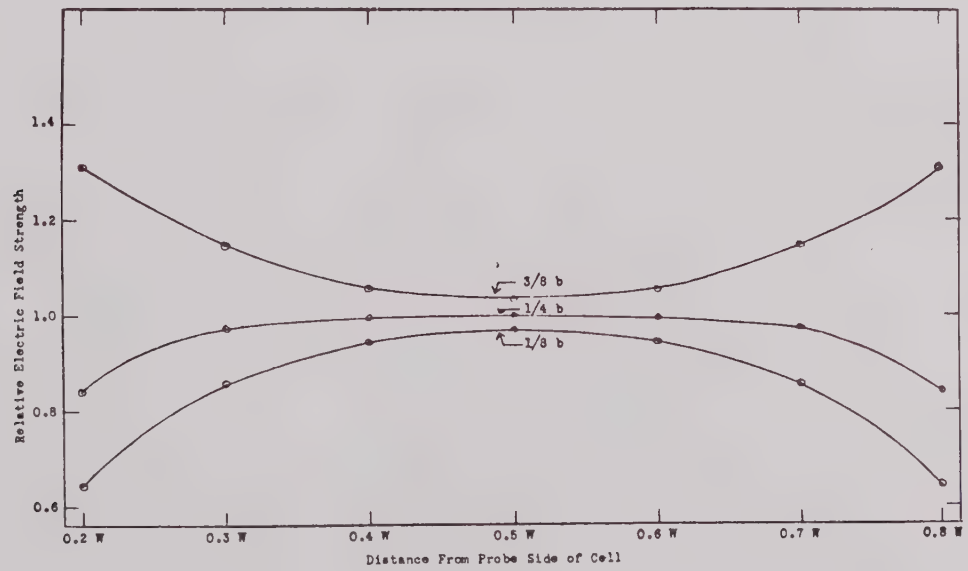

Fig. 8. Relative electric field distribution inside cell. Cross sectional cut through upper half at center of cell. (Form factor Fig. 4.)

the septum or center conductor and increased the field strength 3 dB and 6 dB, respectively, in the regions directly above and below the case. This increase in field strength for a constant test input power must be taken into account when determining the absolute test field, and occurs if significant cross section within the cell is occupied by the EUT.

III. STANDARDIZATION OF THE FIELD INSIDE THE CELLS

The absolute electric field strength E_v at the cell's center between the upper wall and the center conductor is determined using the equation

$$E_v = (P_n R_c)^{1/2}/d \tag{4}$$

where P_n is the net power flowing through the cell, R_c is the real part of the cell's complex characteristic impedance, and d is the separation distance between the cell's upper wall and its center plate or septum.

A brief discussion of the sources of error is given below. The total fractional error ΔE_v in determining the absolute field strength E_v inside the cell is given as

$$\Delta E_v \simeq | \tfrac{1}{2}(\epsilon_R + \epsilon_P) + \epsilon_d + \epsilon_E | \tag{5}$$

where $\epsilon_P = \Delta P_n/P_n$, $\epsilon_R = \Delta R_c/R_c$, $\epsilon_d = \Delta_d/d$, and ϵ_E is the error due to the nonuniformity of E_v determined experimentally by mapping the field distribution in the test region of the cell. Equation (5) was derived by substituting $P_n' = | P_n + \Delta P_n |$, $R_c' = | R_c + \Delta R_c |$, and

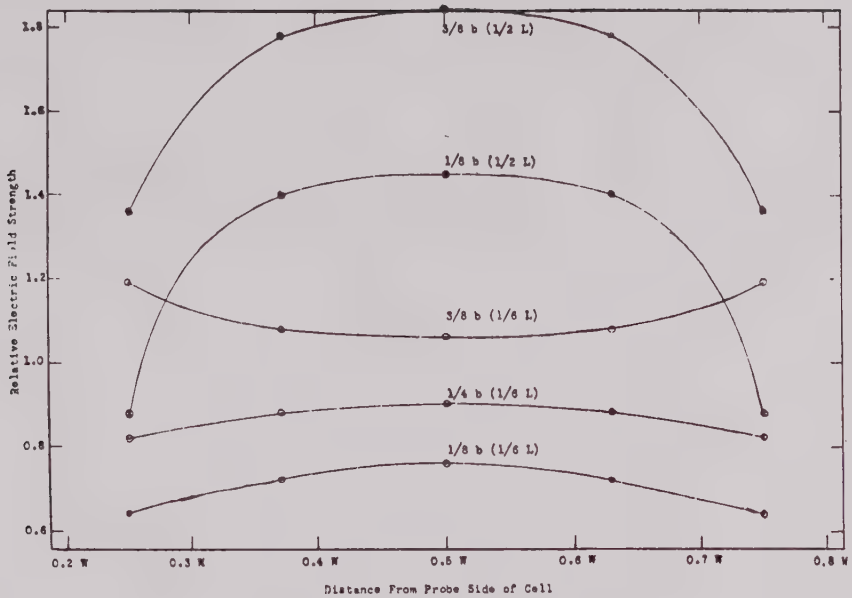

Fig. 9. Relative electric field distribution inside cell with metal case mounted in center of upper half space. Cross sectional cuts at center and off end of case.

$d' = | d + \Delta d |$ into (4) and adding ϵ_E (obtained from E field mapping). Higher order terms contributing to small errors were then dropped in the derivation to arrive at (5).

The error ϵ_P, in determining P_n, is due to uncertainties in coupler calibration, absolute measurement of RF power on the side arm of the coupler, and impedance mismatch between the cell, coupler, RF source, and cell termination. If a precision calibrated coupler and power meter are used and the cell and its termination are impedance matched (VSWR $\leq$ 1.05), ϵ_P should be less than $\pm 5\%$.

The error ϵ_R in determining R_c is a function of the measurement accuracy of the TDR and the impedance loading of the EUT inside the cell. If the EUT occupies a small portion ($\leq 1/5$) of the cross section of the cell, ϵ_R will be small ($\leq 3\%$), and is typically neglected in the calculation of E_n. For larger EUT's (occupying up to 1/3 the cross section of the cell) the impedance loading effect must be determined with the TDR and used to correct R_c when using (4) to calculate E_n. ϵ_R for these cases can be much larger but typically would be less than 10% if the EUT is centered inside the cell. Exceeding the 1/3 load factor is not recommended.

Determining ϵ_E is more difficult. Introducing the EUT inside the cell perturbs the electric field distribution as described in the section on field mapping. This loading factor (increase in E) is determined using the small calibrated probes referred to earlier. If the size of the EUT is less than the 1/5th factor and if care is taken to properly orient or eliminate interconnecting leads to the EUT, ϵ_E can be reduced to less than 6% for cells with the form factor of Fig. 3. Larger EUT's would necessitate measurement of the field distribution around the EUT and a resulting higher estimate of ϵ_E.

TABLE 2
SUMMARY OF MEASUREMENT ERRORS

Source of Error	Percent Uncertainty: Form Factor Fig. 4	Percent Uncertainty: Form Factor Fig. 3
a) Absolute measurement of incident RF power on the side arm of coupler	± 3.0	± 3.0
b) Coupler calibration	± 2.0	± 2.0
ϵ_P, total error in determination of RF power passing through cell	± 5.0	± 5.0
c) Real part of cell complex impedance ϵ_R	± 3.0	± 3.0
d) Cell plate separation ϵ_d	± 1.0	± 1.0
e) Nonuniformity of electric field inside cell ϵ_E	± 6.0	±20.0
maximum field strength error	±11.0	±25.0
	< ± 1.0 dB	< ± 2.0 dB

$$\Delta E_n \sim | \tfrac{1}{2}(0.03 + 0.05) + 0.01 + 0.06 | \times 100 \quad (0.20)$$

The sources of errors for the two form factors are summarized in Table 2.

IV. APPLICATIONS

The block diagrams for making EM susceptibility measurements using the cell are shown in Fig. 10. The EUT is mounted inside the cell in the desired orientation with the interconnecting leads/cables and power cord extended through a side or end wall of the cell, as required. The orientation, size, and type (shielded or unshielded) of interconnecting leads and power cord of the EUT can have a large effect upon the equipment's susceptibility. Tests can be performed with the leads oriented for minimum or maximum field coupling while making the

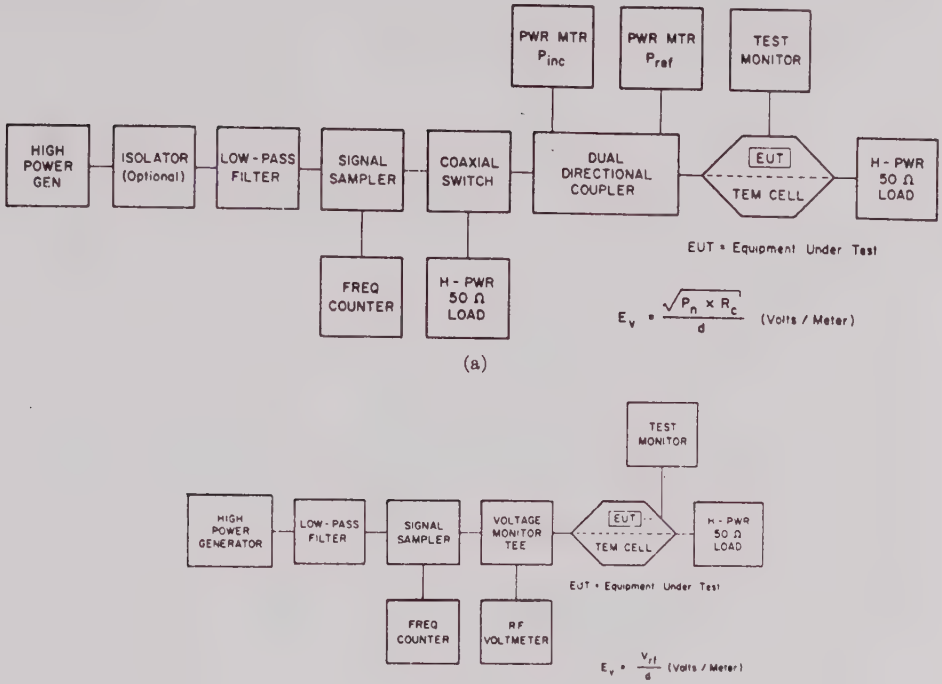

Fig. 10. Block diagrams of system for susceptibility testing of equipment.

susceptibility measurements, thus providing data for evaluating the lead contributions to the overall EUT susceptibility. Minimum lead interaction with the test field is achieved by orienting them in a direction perpendicular to the E field and by properly shielding them. Maximum interaction is achieved by allowing the unshielded leads to sag inside the cell and/or by aligning with the polarization of the test field (leads through top of cell). The susceptibility level for the EUT is determined at frequencies from 1 MHz to the cell multimode frequency by means of the block diagram of Fig. 10(a). The generator output is progressively increased until the EUT's normal operation is noticeably affected. The test field can be further increased until the EUT fails if failure tests are required.

The cells can also be used to calibrate various field detection devices such as hazard probes, field sensors, or small field intensity meters. In this type of operation the device being calibrated is placed inside the cell in a uniform field region. The standard test field is determined by the procedure outlined in Section III, and the field intensity indicated by the instrument is compared with the known value of the standard test field.

Measurements below 1 MHz are made using a voltage monitor tee and RF voltmeter as shown in Fig. 10(b), because directional couplers are not available at these lower frequencies. Directional couplers and power meters are used above 1 MHz because of the ability to monitor impedance variations in the system when installing EUT's inside the cell and orienting them for various tests.

Swept measurements can be made for a fixed orientation of the EUT and its cables using the block diagrams of Fig. 10(a) or (b) assuming the circuit components remain matched over the desired frequency range and have acceptable frequency bandwidth characteristics. When using the system of Fig. 10(b), the input voltage to the cell is monitored directly and (4) becomes,

$$E_v = V_c/d \tag{6}$$

where V_c is the measured input voltage to the cell and is equivalent to $V_c = (P_n R_c)^{1/2}$. The error analysis then involves evaluating the uncertainty in measuring V_c as compared to P_n and R_c, and at the frequencies indicated for these tests, the errors would be about equivalent.

Pulsed RF susceptibility measurements can also be made by replacing the signal source and monitor/detector with an appropriate pulse generator, sampler, and detector (oscilloscope). The exposure level standardization would be similar to that outlined in Section III, but would involve determining the calibration measurement accuracy of the detector, the sampling (coupling) accuracy, and the time domain response of the cell. Additional work needs to be done in this area but it is believed that measurements using pulses with frequency components less than 500 MHz could be made.

The measurement systems shown in Fig. 10(a) and (b) have been used to calibrate or determine the EM sus-

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MP MASTER
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Instruments for Industry, Inc.
731 Union Parkway
Ronkonkoma, Long Island
New York 11779-7414 USA

Voice: 516-467-8400
Fax: 516-467-8558

Email: info@ifi.com
World Wide Web: www.ifi.com